Energy Response Correction for Imaging Detectors Based on Monolithic Crystals

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Abstract

The energy response of an imaging detector based on a monolithic crystal is highly dependent on the position of the gamma ray interaction, which leads to a spectral drift of the imaging detector, known as the spectral drift related to incident position. It deteriorates the energy resolution of the detector and affects the selection of the energy window for imaging, resulting in artefacts in the reconstructed image. Thus, a energy response correction method is proposed to improve the positional consistency of the detector energy response. In both simulation and physical experiments, the method improved the full-energy peak consistency of the monolithic crystal detector, which results in improved energy resolution of the detector, more accurate selection of the energy window, and imaging quality. Especially, in physical experiments, the method converges the peak sites of 365keV energy at each location, which reduced the half-height width of characteristic peak (@365 keV) from 53 to 38 channels, improved the energy resolution by 28.3%, transformed the incomplete mask projection into a complete mask projection, and the signal-to-noise ratio increased from 2.38 to 5.37.

Full Text

Preamble

The energy response of imaging detectors based on monolithic crystals exhibits strong dependence on gamma-ray interaction position, leading to spectral drift that correlates with incident location. This phenomenon, known as position-dependent spectral drift, degrades detector energy resolution and complicates energy window selection for imaging, ultimately causing artifacts in reconstructed images. To address this issue, we propose an energy response correction method to enhance the positional consistency of detector energy response. Both simulation and physical experiments demonstrate that this method improves full-

energy peak consistency in monolithic crystal detectors, resulting in enhanced energy resolution, more accurate energy window selection, and improved imaging quality. In physical experiments particularly, the corrected peak positions converge to 365 keV across all locations, reducing the full width at half maximum (FWHM) of the characteristic peak (@365 keV) from 53 to 38 channels and improving energy resolution by 28.3%. Furthermore, incomplete mask projections are transformed into complete projections, with the signal-to-noise ratio (SNR) increasing from 2.38 to 5.37.

Keywords: Monolithic crystal detector, SiPM array, Spectral drift, Energy response correction method

Introduction

In recent years, advances in inorganic scintillators and optoelectronic sensors have enabled widespread application of scintillator detectors in nuclear physics, particle physics, and radiation imaging [1–12]. Scintillator crystals offer high light yield, short decay time, and excellent energy resolution, making them ideal materials for nuclear instrumentation development [13]. Coded aperture imaging primarily employs two types of scintillator crystals: array crystals and monolithic crystals [14, 15]. Imaging detectors with array crystals are less susceptible to compression effects and can achieve higher spatial resolution, which is primarily determined by the pixel size of the crystal array [16–18]. However, these detectors suffer from photon absorption by reflective layer materials between crystal pixels, and the thickness of crystal arrays significantly reduces energy resolution and detection efficiency [19]. In imaging detectors composed of array crystals coupled to photomultiplier tubes or silicon photomultiplier tubes, spectral peaks vary considerably among individual crystal strips [20, 21].

Compared with array detectors, monolithic crystals offer superior energy resolution and detection efficiency [19]. However, monolithic crystals exhibit truncation and reflection effects of scintillation light that typically result in a useful field of view (UFOV) smaller than the detector’ s effective area. Additionally, reconstruction results from peripheral regions become blended and inseparable, leading to compression effects [19]. In recent years, researchers have employed various algorithms to mitigate compression effects and expand the UFOV in monolithic crystal imaging detectors, including Truncated Centre-of-Gravity (TCOG), Raise-to-Power (RTP; also known as Floating Weight, FW), Least Squares Estimator (LSE), Maximum Likelihood (ML), and Artificial Neural Network (ANN) methods [22–27].

In monolithic crystal imaging detectors, energy response is highly dependent on the location of γ-ray interaction. When gamma rays interact near the crystal edge, the light distribution becomes truncated, and photons within the crystal are affected by structural and physical properties. If the detector surface is covered with absorbing materials, photons will be absorbed [28, 29], resulting in inconsistent energy responses and full-energy peak inconsistency—manifesting as position-dependent spectral drift. This phenomenon degrades energy resolution. In array imaging detectors, inconsistent photomultiplier tube (PMT) gain can cause peak position variations among crystal strips, leading to loss of valid events and reduced detection efficiency [30].

Monolithic crystals may also exhibit uneven energy responses due to non-uniformity in crystal growth and packaging [31]. In positron emission tomography (PET) applications, energy response inconsistency has been identified in thick crystals and corrected specifically for 511 keV pulse signal amplitude, yielding improved energy resolution [32–34]. However, traditional gamma cameras for coded aperture imaging, which rely on two-dimensional projection information, have neglected the influence of particle-detector interaction depth on projection information, thereby reducing imaging quality to some extent. Consequently, Y. Han proposed a correction method for coded gamma cameras based on particle-detector interaction depth to improve imaging quality [35].

If energy response consistency can be improved, imaging quality will be further enhanced. Building upon our research group' s previous simulation experiments [36], this study verifies the phenomenon through physical experiments and establishes an energy response correction model. The model enhances peak position consistency, improves energy resolution, and elevates imaging quality. These improvements are significant for optimizing encoded aperture imaging system performance and expanding applications in nuclear emergency response and radiation monitoring.

2. Material and Methods

We established an imaging detector model using Geant4 and employed a step-scanning method to acquire position-dependent spectral drift data. Based on this model, we developed a radiation imaging system and introduced its electronic and data processing systems. Following the simulation experimental methodology, we confirmed that position-dependent spectral drift also exists in physical experiments, where the effect is even more pronounced.

2.1. Simulation

To investigate position-dependent spectral drift, we constructed a monolithic scintillator-based imaging detector model using GEANT4 software, as illustrated in Fig. 1c [Figure 1: see original paper]. The model employs a monolithic LaBr3(Ce) crystal renowned for its exceptional density, energy resolution, light yield, and decay time characteristics. Fig. 1 depicts the detector structure and step-scanning process. The detector incorporates a 51 mm × 51 mm × 5 mm LaBr3(Ce) crystal coated with a 0.3 mm Teflon foil serving as the front diffuse reflective layer. The scintillator is surrounded and encapsulated by a 0.5 mm aluminum foil acting as the specular reflective layer [20]. A 3 mm glass layer (reflectivity 1.5) and 0.1 mm optical grease (reflectivity 1.41) are placed between the crystal bottom and the silicon photomultiplier (SiPM) array. The SiPM model used is the Micro-30035-TSV manufactured by ONSEMI, featuring a 16 × 16 array with a 3.07 mm × 3.07 mm sensitive area and a 3.15 mm × 3.15 mm package area [20].

The physical property parameters of lanthanum bromide crystals primarily include emission spectrum, light yield, decay time constant, refractive index, and intrinsic resolution. The emission spectrum of LaBr3(Ce) crystals varies with cerium content. As Ce concentration increases, light yield changes slightly while decay time shortens. The decay time constant generally comprises fast and slow components. Since the fast decay component of LaBr3:5% Ce crystals accounts for 97% of the total, we configured the decay time constant to include only the fast component, set at 15 ns with a yield value of 1 [37, 38]. The crystal' s light yield (scintillation yield, SCY) is set to 63,000/MeV, and its refractive index is set to 1.85 [38]. In GEANT4, the crystal model' s emission spectrum is based on experimental data [39].

A distinctive feature of lanthanum bromide crystals is the presence of radioactive materials 138La and 227Ac within the crystal lattice. These radionuclides endow LaBr3(Ce) crystals with intrinsic radioactivity, yielding a background energy spectrum that differs slightly from the natural background spectrum. In the low-energy region (0–1800 keV), the background spectrum primarily originates from gamma transitions of 138La (789–1436 keV). For background spectrum simulation, we calculate the total 138La activity based on detector crystal volume and randomly distribute it throughout the crystal (138La volume activity: 1.52 Bq/cm^3) [40, 41], resulting in a total activity of 19.7 Bq. Due to the crystal' s small size, its absorption capacity for 789 keV and 1436 keV gamma rays is limited, minimally impacting imaging results. In the high-energy region (1800–2800 keV), radiation primarily originates from 227Ac and high-energy environmental background radiation. Since the total count of high-energy radiation is low, its impact on energy spectrum measurement and imaging results is minimal.

In simulation studies, optical photon transport can be divided into two main components. The first involves photon transport within the medium, where users define material parameters. These parameters primarily include emission spectra, scintillation yield, intrinsic resolution, and fast decay components of the scintillator, which critically determine optical photon production and transport through the medium. The second component involves photon transport between different media, requiring specification of surface parameters. Key surface parameters include type, finish, efficiency, reflectivity, and reflectivity type, which control physical interactions of optical photons at media interfaces.

The simulation program primarily utilizes the FTFP_{BERT} modular physics process, replacing the electromagnetic interaction process with the standard electromagnetic process G4EmStandardPhysics_{option1}. Additionally, the program incorporates the G4OpticalPhysics optical process. G4EmStandardPhysics_{option1} encompasses various fundamental electromagnetic interactions, including the photoelectric effect, Compton scattering, pair production, Coulomb scattering, and bremsstrahlung. The implemented optical processes include scintillation, Cherenkov radiation, Rayleigh scattering, Mie scattering, refraction, and reflection.

The effective detection area of the monolithic crystal imaging detector is artificially divided into 441 blocks. A point source is simulated using the Class PrimaryGeneratorAction, with gamma-ray emission position and direction set 180 mm in front of the imaging detector. The I-131 radioactive source is positioned within a tungsten shielding canister on the detector' s incident side. The tungsten canister features a collimation hole, enabling γ-rays from I-131 to perpendicularly irradiate the detector. Employing a step-scanning method, each block is scanned to obtain the detector response for all ray entry positions. When gamma rays enter the detector from a specific block and interact with the scintillator to produce photons, the SiPM array converts these photons into electrical signals. Signals from 256 SiPMs are summed to serve as the detector' s energy response. The summed SiPM array signal is then statistically processed to obtain the γ-ray spectrum for each incident block. Subsequently, the peak channels of gamma-ray spectra for each incident region are extracted. Since events occurring near the crystal center produce relatively complete light distributions, while gamma-ray interactions at the crystal edge result in truncated light distributions, the peak channel of the spectrum in Block (00,00) is used as the standard reference.

In simulation experiments, we obtained gamma-ray energy spectra for ten common energies across various detector blocks. Ten distinct spectral peaks are clearly visible, confirming the feasibility of our model [36]. Isolating the characteristic peak at 365 keV yields Fig. 1b. Notably, significant position-dependent spectral drift occurs within the detector from Block (00,00) to Block (10,10), becoming more pronounced with increasing energy. Given the limited variety of radiation sources available in our laboratory, to rigorously compare simulation with experimental results, we extracted the spectral channels corresponding to the 365 keV peak from the simulation dataset. This extraction provided the 365 keV peak channel across various blocks for subsequent analysis, as shown in Fig. 1d. The correlation between the 365 keV peak channel and spatial position indicates minimal displacement at the center, increasing toward the periphery. This suggests a positive correlation between displacement magnitude and proximity to the central axis—the peak displacement is smallest at the center and gradually increases toward the edges.

This phenomenon arises from gamma-ray interactions with the crystal lattice, causing ionization and excitation of lattice atoms followed by photon emission during de-excitation. Photon interactions with the crystal include absorption, refraction, and reflection processes, with backscattering playing a more significant role in peripheral regions. Additionally, photons traversing the crystal are modulated by crystal structure and physical properties, leading to photon flux attenuation. This results in spatial heterogeneity of the detector' s intrinsic response characteristics, producing position-dependent energy responses to gamma rays.

2.2. Experiment

Fig. 2a [Figure 2: see original paper] illustrates the radiation imaging system, which primarily consists of an encoding plate (MURA-11), imaging detector, electronic system, Jetson Xavier NX, and display unit. The imaging detector comprises a LaBr3(Ce) crystal coupled to an SiPM array. This study utilizes the ARRAYJ-30035-64P SiPM array model manufactured by Onsemi. By assembling four such arrays, a 16×16 detector array is formed, yielding 256 channels of output signals. The ARRAYJ-30035-64P consists of 3 mm $\times$ 3 mm J-series SiPMs arranged in an 8×8 array. Four SiPM arrays are mounted to the front of the interface board via connectors on the back, leaving a 1 mm gap between arrays to facilitate detector packaging. The back of the interface board comprises four pairs of connectors for bias voltage input and initial signal readout of the SiPM arrays. All sensor substrates (cathodes) are combined to form a common I/O. After completing internal detector packaging, the assembly is fixed to the detector housing through mounting holes at the four corners of the interface board. In the interface board design, due to limited copper plating and light leakage from connectors, black tape is applied for additional light shielding to achieve better optical isolation.

The electronic system comprises a Symmetric Charge Division Circuit (SCDC), Amplitude Time Convert Circuit (ATCC), and Digital Signal Processing Circuit (DSPC). The ATCC initially employs an AD8066 operational amplifier to perform signal summation and amplification, scaling the signal to a suitable amplitude for input into a hysteresis comparator circuit. The comparator utilizes the TLV350 device, and the hysteresis comparison circuit shapes the nuclear pulse signal into a rectangular pulse signal. The 256-channel signals read out from the SiPM array detector are divided into 32-channel signals through the summing circuit and input to the DSPC via an FPC interface for FPGA acquisition. The DSPC incorporates a Xilinx 7 Series core board along with a system power board. The core board captures the 32-channel rectangular pulse signals output by the conditioning board through its 32 I/O ports. A single channel signal that has undergone A/D conversion is acquired by the FPGA for filtering, shaping, peak value extraction, and energy spectrum analysis. The 33-channel signal data (32 rectangular pulse signals and 1 ADC channel) processed by the core board are transmitted via Ethernet to the Jetson Xavier NX for further processing. The Jetson Xavier NX, NVIDIA' s edge computing platform, deploys 32-FCNN localization algorithms and Maximum Likelihood Estimation algorithms (MLEM), enabling parallel computation for algorithm acceleration. Ultimately, reconstructed images and radioactive source information are displayed on the monitor.

In physical experiments analogous to simulations, an I-131 source is positioned 180 mm from the detector. A step-scanning method is employed, where radiation perpendicularly irradiates the detector surface through a collimator. The detector captures energy responses at different incident positions. During step-scanning, a collimator with a 2.5 mm hole diameter, 33 mm overall diameter, and 55 mm thickness is used to collimate gamma rays from I-131. The detector's effective detection area is then gridded, uniformly divided into 441 blocks as in the simulation experiment. The I-131 source (activity: 0.1 mCi) is placed above the collimator, marking the incident position as (x,y). Each point is measured for 4 minutes, and the summed signal Vxy from the SiPM array at position (x,y) is acquired through the multi-channel signal acquisition board. Finally, the energy spectrum Exy at the incident position is statistically derived from signal Vxy using the host computer, completing a single step-scan measurement. The entire step-scanning process involves 441 measurement points, with a total duration of 29.4 hours.

Fig. 2b illustrates the distribution of 365 keV characteristic peaks for Block (00,00) and Block (10,10) in the physical experiment. The experimental data closely align with Monte Carlo (MC) simulation results. Variation in pulse height channel addresses is notably pronounced due to different radiation incident positions. During gamma-ray interaction with the crystal, ionization and excitation of crystal atoms occur, with photon emission during de-excitation. These photons may be absorbed, refracted, and reflected by the crystal, with edge positions being more significantly affected by backscattering. Moreover, photon propagation within the crystal is influenced by its structure and physical properties, causing light loss. This results in inconsistent energy responses of monolithic crystal detectors. The overall peak position pattern indicates that spectral drift related to incident position is minimal near the center and more severe toward peripheral positions, similar to simulation results.

In the physical experiment, the degree of peak position offset was more severe, reaching 84 channels. Although SiPMs exhibit some temperature drift, the entire experimental process was conducted at room temperature, with the signal processing circuit board and FPGA chip maintaining essentially constant temperature. Therefore, spectral drift caused by temperature can be considered negligible. This result is attributed to differences in crystal uniformity. In simulation experiments, the LaBr3(Ce) crystal is isotropic with perfectly uniform properties throughout. Actual LaBr3(Ce) crystals lack such uniformity, manifesting in specific growth directions and variations in Ce doping concentrations at different locations. These differences cause inhomogeneous anisotropic photon transmission and variations in photon emission numbers for scintillation events of the same energy. These inconsistencies affect detector pulse signal amplitude, thereby influencing energy resolution. Additionally, differences in crystal packaging contribute to this result. In simulation programs, not only is the crystal itself perfectly uniform, but the crystal surface packaging is also consistently applied everywhere—such consistency is difficult to achieve experimentally. Differences in LaBr3(Ce) surface packaging make the light transmission process non-uniform and asymmetric. When charged particles are incident from different positions on the crystal surface, geometric factors affect photon transmission within the crystal, eventually resulting in different peak positions.

3. Results and Discussion

Based on the characteristics of this class of detectors, we propose a method and principle for an energy response functional correction matrix. We evaluate and discuss correction effects on peak consistency from four aspects: full-energy peak consistency, energy resolution, encoded images, and reconstructed image quality.

3.1. Correction Method

In preliminary simulation studies, we extracted peak channels of each full-energy peak in the energy range of 300 keV to 2000 keV for various blocks. Since a linear relationship exists between peak channel and peak energy, a linear relationship should also exist between characteristic peaks in each block [36]. Therefore, in physical experiments, we can similarly employ a functional correction matrix to improve full-energy peak consistency. However, the functional correction matrix requires recalibration. Thus, we investigated the linear relationship between the full-energy peak of the central Block (00,00) and other blocks through physical experiments.

Since step-scanning experiments impose specific requirements on radiation source type, activity, and size, our laboratory could only provide I-131 meeting these requirements. Additionally, because calibration of the functional correction matrix requires full-energy peaks at two or more energies, we selected the two characteristic peaks of I-131 at 284 keV (branching ratio 6.12%) and 365 keV (branching ratio 81.5%) for matrix calibration. Fig. 3a demonstrates the linear relationship between the 284 keV and 365 keV characteristic peaks of the central Block (00,00) and peripheral Block (09,08) and Block (10,10) in physical experiments. The linear relationship formula between Block (00,00) and Block (10,10) is y(10,10) = 0.98x - 36.29, with k(10,10) = 0.98 and b(10,10) = -36.29. The linear relationship formula between Block (00,00) and Block (09,08) is y(09,08) = 1.02x - 38.71, with k(09,08) = 1.02 and b(09,08) = -38.71. Thus, the functional correction matrix is composed of coefficients (k,b) from these linear equations.

We establish a linear parameter fitting line between the spectral channel address of Block (i, j) and that of the central Block (00,00) detector, with the linear relationship y(i,j) = k(i,j)x + b(i,j). Here, y(i,j) represents the peak channel address for Block (i, j), x indicates the peak channel for the central Block (00,00), k(i,j) denotes the slope for Block (i, j), and b(i,j) represents the y-intercept for Block (i, j). Ultimately, a functional correction matrix (k(i,j),b(i,j)) is obtained, as shown in Eq. (1).

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(k-10,10, b-10,10) (k-10,09, b-10,09) ... (k-10,-09, b-10,-09) (k-10,-10, b-10,-10)
...
(k00,00, b00,00) ...
...
(k10,10, b10,10) (k10,09, b10,09) ... (k10,-09, b10,-09) (k10,-10, b10,-10)
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Based on the functional relationship between incident position and energy discovered in this study, we propose an energy response functional correction matrix to correct energy response and improve full-energy peak consistency. First, a step-scanning method calibrates the detector' s correction matrix. Gamma rays are incident perpendicularly onto the detector through a collimator, and the SiPM array response signals are summed and statistically analyzed to obtain energy spectra, from which full-energy peaks and coordinate information are extracted. Using a linear function, we obtain coefficients for each block' s peak channel relative to the central block' s peak channel, thereby acquiring the detector' s complete energy response functional correction matrix. Finally, using the coordinate information of ray-detector interactions and based on the "look-up table" principle, we identify the correction coefficients corresponding to the coordinates in the energy response functional correction matrix, thereby correcting the peak channel for each interaction event, as shown in Fig. 3c [Figure 3: see original paper]. In Fig. 3c, E(i,j) is the uncorrected peak address, (k, b) constitutes the functional correction matrix, and E (i,j) is the corrected peak address.

This imaging system utilizes a ray localization algorithm based on neural networks to obtain positional information of incident radiation [28]. The principle is that when rays interact with the detector, the SiPM at the interaction point receives the strongest pulse signal intensity, while signal strength gradually decreases at other SiPM locations as scintillation light propagates through the crystal. Therefore, ray position can be determined based on light intensity distribution across the SiPM array. In this imaging system, the 256-channel SiPM signals are summed and converted into 32-channel signals, which serve as input data for a fully connected neural network to perform ray localization, yielding positional information. The neural network model structure includes one input layer, two hidden layers, and one output layer. The input layer receives 32-channel signals, while the output layer provides the coordinates (X,Y) of the interaction position between incident rays and the crystal. The activation function used is ReLU. With this approach, the intrinsic spatial resolution of the radiation imaging system can reach 2.67 mm.

3.2. Correction Results

To better compare uncorrected and corrected results from both simulation and physical experiments, this study uses characteristic gamma rays emitted by I-131 as the measurement object for both simulation and physical experiments. Correction results are discussed in terms of uncorrected and corrected peak position consistency, energy resolution, encoded images, and reconstructed image quality.

Regarding full-energy peak consistency, we obtained the energy response functional correction matrix separately from simulation and physical calibration experiments and corrected the energy response for both simulated and physical experiments, resulting in significant improvement in full-energy peak consistency. Fig. 4a [Figure 4: see original paper] illustrates the corrected 365 keV peak for various incident blocks in the simulation experiment, while Fig. 4b shows the same for the physical experiment. The figures demonstrate that peaks in edge blocks have been substantially corrected in both simulation and physical experiments, with full-energy peak consistency markedly enhanced and essentially converging to uniformity. Additionally, within the 365–1332 keV energy range, simulation experiment results are well-fitted to the energy response functional correction matrix [36]. The energy response functional correction matrix is designed to channel the 284 keV and 365 keV energies of I-131 in the physical experiment, consequently reducing peak channel error to zero channels in the physical experiment.

Due to inconsistent responses of uncorrected peaks, detector energy resolution varies. When incident gamma rays are predominantly absorbed by edge blocks, detector energy resolution decreases. Conversely, when the central block primarily absorbs incoming rays, energy resolution improves. Thus, enhancing full-energy peak consistency can improve energy resolution to a certain extent. The energy response functional correction matrix obtained separately from simulation and physical calibration experiments corrects energy response in both simulated and physical experiments, yielding improved energy resolution. Fig. 4c and Fig. 4d show energy resolution at 365 keV before and after correction for simulation and physical experiments, respectively. Comparison reveals that the corrected gamma-ray spectrum exhibits narrowed FWHM, obviously increased peak count, and improved energy resolution. In simulation experiments, the FWHM of the 365 keV characteristic peak was reduced from 38 channels to 32 channels, improving energy resolution by 18.8%. In physical experiments, the FWHM of the 365 keV characteristic peak was reduced from 53 channels to 38 channels, improving energy resolution by 28.3%. Improved energy resolution of the imaging detector plays a key role in energy window data selection and reconstructed image quality enhancement.

In coded aperture gamma imaging system applications, data selection is based on the energy window. Due to inconsistent uncorrected peak responses, detection efficiency is reduced and real events are lost, affecting image quality. In severe cases, this can lead to incomplete projected images and ultimately imaging failure, especially when incident rays are mainly absorbed by edge blocks. Therefore, correcting full-energy peak consistency in the detector' s effective detection area is necessary to improve imaging quality.

In this study, both simulation and physical experiments utilized an I-131 radioactive source (t1/2 = 8.02 d) with an activity of 0.1 mCi. The I-131 point source center, encoding board collimator, and imaging detector are aligned horizontally on the same axis. The distance between the I-131 point source and detector is 80 cm, and the distance between the encoding board collimator and detector is 5 cm. The MURA array can be represented by a matrix Bij, where r denotes the number of rows (or columns) in the matrix, which is a prime number. Bij = 1 indicates an open aperture, and Bij = 0 indicates a closed aperture

[42]. The nested MURA coded aperture structure is derived from the MURA (N × N) by expanding the MURA coded aperture in a centrally symmetric manner to nine times its original size, resulting in the Loop MURA (3N × 3N). Subsequently, a coded aperture of size (2N-1)×(2N-1) at the central position is selected to serve as the Nested MURA [42].

After radiation interacts with the crystal, a neural network localization algorithm acquires the encoded image on the detector. Fig. 5a [Figure 5: see original paper] and Fig. 5b represent uncorrected and corrected encoded images from the physical experiment, respectively. In Fig. 5a (uncorrected encoded image), data loss is observed in the upper right and lower left corners, with more significant loss in the lower right corner. This is attributed to loss of true events in these blocks as shown in Fig. 2b, leading to imprecise energy window data. The uncorrected encoded images in the physical experiment are severely hampered by data loss, rendering image reconstruction infeasible. In addition to event positions causing peak inconsistencies, SiPM manufacturing processes cannot guarantee identical performance for each device. The response of the SiPM array, signal acquisition, and readout are not perfectly synchronized, which further aggravates full-energy peak inconsistency and reduces the amount of effective encoded image data. The corrected encoded images are more complete, enabling clearer image reconstruction.

When the radioactive source is located at the center of the imaging detector' s useful field of view (UFOV), most valid information is collected in the central detector area. An incomplete encoded image will not lead to image reconstruction failure, and accurate reconstruction of the radioactive source position remains possible. In this case, full-energy peak inconsistencies can introduce artifacts in the reconstructed image, reducing the signal-to-noise ratio (SNR) and affecting reconstruction quality. However, when the radioactive source is located at the edge of the imaging detector' s UFOV, most valid information is concentrated in the peripheral detector area. Inconsistent full-energy peaks can cause severe loss of valid information, leading to deviations in the reconstructed radioactive source position or even complete imaging failure. The corrected peak channel eliminates data outside the energy window and improves detector detection efficiency. Simultaneously, it enhances imaging detector energy resolution, significantly improving SNR from 2.38 to 5.37—an increase of 125.6%. Fig. 5 demonstrates that the uncorrected imaging detector' s poor energy resolution causes data outside the energy window to be recognized as valid data, resulting in low SNR and artifacts in the reconstructed image. The corrected reconstructed image shows improved SNR, reduced or eliminated artifacts, and enhanced reconstruction quality.

4. Conclusions

This study reveals that not only crystal arrays but also monolithic crystals exhibit energy response inconsistency. Different gamma-ray incident positions can cause variations in energy deposition in monolithic crystal detectors, leading to energy response inconsistency. This reduces energy resolution and affects radiation imaging system imaging quality.

By performing step-scanning to obtain full-energy peaks at different incidence positions and based on the linear relationship between each block's peak channel and the central block' s peak channel, we obtain the detector' s energy response functional correction matrix. A 32-FCNN localization algorithm positions incident rays and obtains positional information. According to this positional information, corresponding correction coefficients from the energy response functional correction matrix are matched, thereby correcting the detector' s energy response.

Correction results demonstrate that this method can effectively improve energy response consistency, enhance energy resolution, and improve imaging quality. In simulation experiments, this method improves full-energy peak consistency, decreasing the FWHM of the 365 keV characteristic peak from 33 channels to 28 channels, improving energy resolution by 15.2% and enhancing detection efficiency. In physical experiments, this method improves full-energy peak consistency of the monolithic crystal imaging detector and makes peaks evenly distributed across the detector plane. Regarding energy resolution, the method reduces FWHM from 53 channels to 38 channels at the 365 keV characteristic peak, increasing energy resolution by 28.3%. For image reconstruction, the method reduces artifacts in reconstructed images, improves SNR from 2.38 to 5.37, and even transforms incomplete encoded images into fully encoded images to achieve more accurate image reconstruction.

The method proposed in this study minimizes or eliminates the impact of energy response inconsistencies, enhances detector energy resolution, enables more accurate energy window selection in imaging detectors, and improves image quality. This is of great significance for improving nuclide identification accuracy and enhancing energy spectrum imaging quality.

References

[1] S. Sun, Y. Liu, X. Ouyang et al., Near-field high-resolution coded aperture gamma-ray imaging with separable masks. Nucl Instrum Meth A 951, 163001 (2020). doi: 10.1016/j.nima.2019.163001 [2] R. Pani, R. Pellegrini, P. Bennati et al., Investigation on a small FoV γ camera based on LaBr3:Ce continuous crystal. Nucl Phys B-Proc Sup. 197, 202-205 (2009). doi: 10.1016/j.nuclphysbps.2009.10.067 [3] R. Wojcik, S. Majewski, High spatial resolution γ imaging detector based on a 5" diameter R3292 Hamamatsu PSPMT. IEEE T Nucl Sci. 45, 487-491 (1998). doi: 10.1109/23.682432 [4] X.L. Shen, P. Gong, X. B. Tang et al., Encoding methods matching the 16$\times$16pixelCZTdetectorofacodedaperturegammacamera.NuclSciTech.31, 92(2020).doi : CNKI : SUN : HKXJ.0.2020−09−008[5]H.J.Kim, H.Back, K.S.Joo., Developmentofawirelessradiationde photomultiplier(SiPM).NuclEngTechnol.52, 456−460(2019).doi : 10.1016/j.net.2019.07.027[6]D.Renker., Ge modeavalanchephotodiodes, history, propertiesandproblems.NuclInstrumMethA567, 48−

56(2006).doi : 10.1016/j.nima.2006.05.060[7]H.Y.Zhu, J.L.Lou, Y.L.Ye, etal., TwoannularCsI(Tl)detectorar
165(2023).doi : 10.1007/s41365−023−01319−8[8]H.Yang, X.Y.Zhang, W.G.Gu, etal., Anovelmethodforgamm
levelandintermediate − levelradioactivewaste.NuclSciTech.34, 199 −
213(2023).doi : 10.1007/s41365−023−01236−w[9]H.Cheng, B.H.Sun, L.H.Zhu, etal., Intrinsicbackgroundrad
10.1007/s41365−020−00812−8[10]M.Grodzicka, M.Moszynski, T.Szczesniak, etal., Energyresolutionofsma
10.1088/1748−0221/8/02/P02017[11]Z.Lin, B.Hautefeuille, S.Jung, etal., Thedesignofascintillationsystem
169(2020).doi : 10.1016/j.net.2019.07.005[12]H.Miyamoto, I.Minoura, K.Okamoto, etal., SiPMinterdisciplin
90(2012).doi : 10.1016/j.nima.2011.11.078[13]R.G.Shi, Y.Chen, M.F.Wei., Leastsquaresestimatealgorithmbe
12029(2018).doi : 10.1088/1748−0221/13/12/P12029[14]A.Fabbri, D.Sacco, P.Bennati, etal., Studyofposition
Cecontinuous, scintillationcrystalformedicalapplications.JInstrum.8, 12010−
12010(2013).doi : 10.1088/1748−0221/8/12/P12010[15]W.Siman, S.C.Kappadath, Performancecharacterist
3444(2015).doi : 10.1118/1.4718874[16]H.Kubo, KHattori, CIdaetal., Developmentofagammacamerabasedon
array of LaBr3(Ce) scintillator pixels coupled to a 64-channel multi-anode PMT. IEEE NUCL SCI CONF R. 4569-4573 (2007). doi: 10.1109/NSS-MIC.2007.4437127 [17] T Fujita, J Kataoka, T Nishiyama, et al., Two-dimensional diced scintillator array for innovative, fine-resolution gamma camera. NUCL INSTRUM METH A. 21, 262-268 (2014). doi: 10.1016/j.nima.2014.04.060 [18] R Pani, R Pellegrini, F Scopinaro, et al., Scintillating array gamma camera for clinical use. NUCL INSTRUM METHODS. 392, 295-298(1997). doi: 10.1016/S0168-9002(97)00268-4 [19] W. Lu, L. Wang, Y. Yuan, et al., Monte Carlo simulation for performance evaluation of detector model with a monolithic LaBr3(Ce) crystal and SiPM array for γ radiation imaging. Nucl Sci Tech. 33, 165-176 (2022). doi: 10.1007/s41365-022- [20] Y. Li, C. Wang, L. Y. Liu, et al., Development and performance calibration of position sensitive detector based on LaBr3(Ce) crystal coupled with SiPM. Nucl Tech. 45, 53-58 (2022). doi: 10.11889/j.0253-3219.2022.hjs.45.070401 (in Chinese) [21] Y. Li, Q. Wang, X. C. Huang, et al., Detector design and performance test for coded camera of large area and high sensitivity. Nucl Tech. 43, 33-38 (2020). doi: 10.11889/j.0253-3219.2020.hjs.43.050402 (in Chinese) [22] V. O. Cencelli, F. D. Notaristefani, A. Fabbri, et al., A gamma camera with the useful field of view coincident with the crystal area. IEEE Nucl Sco Conf R. 1885-1990 (2009). doi: 10.1109/NSSMIC.2009.5402162 [23] A. Fabbri, P. Bennati, V.O. Cencelli, et al., A new iterative algorithm for pixilated and continuous scintillating crystal. Nucl Instrum Meth A. 648, 79-84 (2011). DOI: 10.1016/j.nima.2010.12.136 [24] R. G. Shi, Y. Chen, X. J. Dang, et al., Experimental evaluation of reconstruction algorithms for scintillation crystal array based on charge projection readout. Nucl Instrum Meth A. 937, 117-124 (2019). doi: 10.1016/j.nima.2019.05.064 [25] W. Lee, G. Cho, S. W. Lee, et al., Simulation of maximum-likelihood position estimation in small gamma camera with position-sensitive photomultiplier tube (PSPMT). IEEE Nucl Sci Conf R. 4, 1915-1918 (2001). doi: 10.1109/NSS-MIC.2001.1009198 [26] P. Bruyndonckx, S. Léonard, S. Tavernier, et al., Neural network-based position estimators for PET detectors using monolithic LSO blocks. IEEE T Nucl Sci. 51, 2520-2025 (2004). doi: 10.1109/TNS.2004.835782 [27] W. Lu, H. W. Zhang, M. Z. Liu, et al., Generalization ability of a CNN γ-ray localization model for radiation imaging. Nucl Sci Tech. 34, 185 (2023). doi: 10.1007/s41365-023-01323-y [28]

S Seifert, H T V Dam , J Huizenga,et al., Monolithic LaBr3:Ce crystals on silicon photomultiplier arrays for time-of-flight positron emission tomography. PHYS MED BIOL.57, 2219-2233(2012). doi: 10.1088/0031-9155/57/8/2219 [29] M C Maas, D R Schaart, L D J Vand,et al., Monolithic scintillator PET detectors with intrinsic depth-of-interaction correction. PHYS MED BIOL. 54, 1893(2009). doi: 10.1088/0031-9155/54/7/003 [30] Y. Li, Q. Wang, X. C. Huang,et al.,Detector design and performance test for coded camera of large area and high sensitivity. Nucl Tec. 43, 6(2020). doi: CNKI:SUN:HJSU.0.2020-05-005(in Chinese) [31] P. X. Nie, T. Zheng, Z. W. Zhao,et al., Incident Position Dependence of the Energy Response of CsI(Tl) to Charged Particle. Nucl Elec and Dete Tec. 31, 601-605(2011). doi: 10.3969/j.issn.0258-0934.2011.06.003(in Chinese) [32] M Freire, A Gonzalez-Montoro, F Sánchez, et al., Calibration of Gamma Ray Impacts in Monolithic-Based Detectors Using Voronoi Diagrams. IEEE T RAD PLA.54, 350-360(2020). doi: 10.1109/TRPMS.2019.2947716 [33] R Pani, M Bettiol, E Preziosi, et al., A Novel Method for γ-photons Depth-of-Interaction Detection in Monolithic Scintillation Crystals. IEEE T NUCL SCI.63, 2487-2495(2016). doi: 10.1109/TNS.2016.2539287 [34] G Borghi, V Tabacchini, D R Schaart. Towards monolithic scintillator based TOF-PET systems: practical methods for detector calibration and operation. PHYS MED BIOL.61, 4904-4928(2016). doi: 10.1088/0031-9155/61/13/4904 [35] Y. Han, X. Jiang, H. H. Tang, et al., YSO coded aperture camera based on depth of interaction for location correction. Rad Detec Tech Meth.7, 589-598(2023). doi: 10.1007/s41605-023-00415-y. [36] H. X. Li, L. Wang, W. Lu, et al., A study on "position-energy" response correction method based on monolithic crystal coupled SiPM array. Nukleonika. 69, 169-176 (2024). doi: 10.2478/nuka-2024-0024 [37] E.V.D. van Loef, P. Dorenbos, C.W.E. van Eijk, et al., Scintillation properties of LaBr3:Ce3+ crystals: fast, efficient and highenergy-resolution scintillators. Nucl Instrum Meth A. 486, 254–258 (2002). doi: 10.1016/S0168-9002(02)00712-X [38] J. Glodo, W.W. Moses, W.M. Higgins et al., Effects of Ce concentration on scintillation properties of LaBr3:Ce. IEEE Nucl Sci Conf R. 52, 1805–1808 (2005). doi: 10.1109/TNS.2005.856906 [39] S. Raffaele, P. Roberto, P. Rosanna et al., MgO reflectance data for Monte Carlo simulation of LaBr3Ce scintillation crystals. Nucl Instrum Meth A. 701, 44–53 (2013).doi: 10.1016/j.nima.2012.10.060 [40] H. Cheng, B. H. Sun, L. H. Zhu, et al., Intrinsic background radiation of LaBr3(Ce) detector via coincidence measurements and simulations. Nucl Sci Tech. 31, 33-34 (2020). doi: 10.1007/s41365-020-00812-8 [41] C. L. Zhao, Y. P. Li, L. H. Chen, et al., Experimental Study of Lanthanum Bromide Detector in the Gamma ray Imaging. Appl Mech Mater. 336, 373-378 (2013).doi: 10.4028/www.scientific.net/AMM.336-338.373 [42] S. R. Gottesman, E. E. Fenimore. New family of binary arrays for coded aperture imaging. Appl Optics. 28, 4344-4352 (1989).doi: 10.1364/AO.28.004344

Note: Figure translations are in progress. See original paper for figures.